LDCM Preliminary Thermal Trades

Prepared by:

Robert Ryan
Mary Pagnutti
Slawomir Blonski
Joe Spruce

Lockheed Martin Space Operations
Stennis Programs

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Thermal Band Background

- **Problem**
  - The expected cost of adding thermal bands to the next generation LDCM could be significant. Can new technologies be implemented to allow for a low cost useful alternative?

- **Approach**
  - Investigate both traditional cooled cross-track scanners and new architectures *(cooled and uncooled)* which could enable a low cost thermal capability

Heritage Landsat Thermal Specifications

- **MSS and TM**
  - GSD 120 m
  - NEDT 1.4 °K *(MSS);* 0.5 °K *(TM)*
  - Spectral Range 10.4-12.6 μm (MSS); 10.4-12.5 μm *(TM)*
  - Radiometric Accuracy <10% *(TM)*
  - Dynamic Range 6 bits *(MSS);* 8 bits *(TM)*

- **ETM+**
  - GSD 60 m
  - NEDT 0.5 °K
  - Spectral Range 10.4-12.5 μm
  - Radiometric Accuracy 2-5%
  - Dynamic Range 8 bits - 2 different gain settings

Thermal Application GSD Comments

Landsat Data Continuity Mission

- **Many thermal applications have utilized Landsat MSS/TM heritage 120 m GSD**

- **Conversations with thermal community indicate that 120 m GSD is the maximum useful pixel size for many Landsat thermal applications**
  - Cloud detection
  - Volcanology
  - Water body temperature

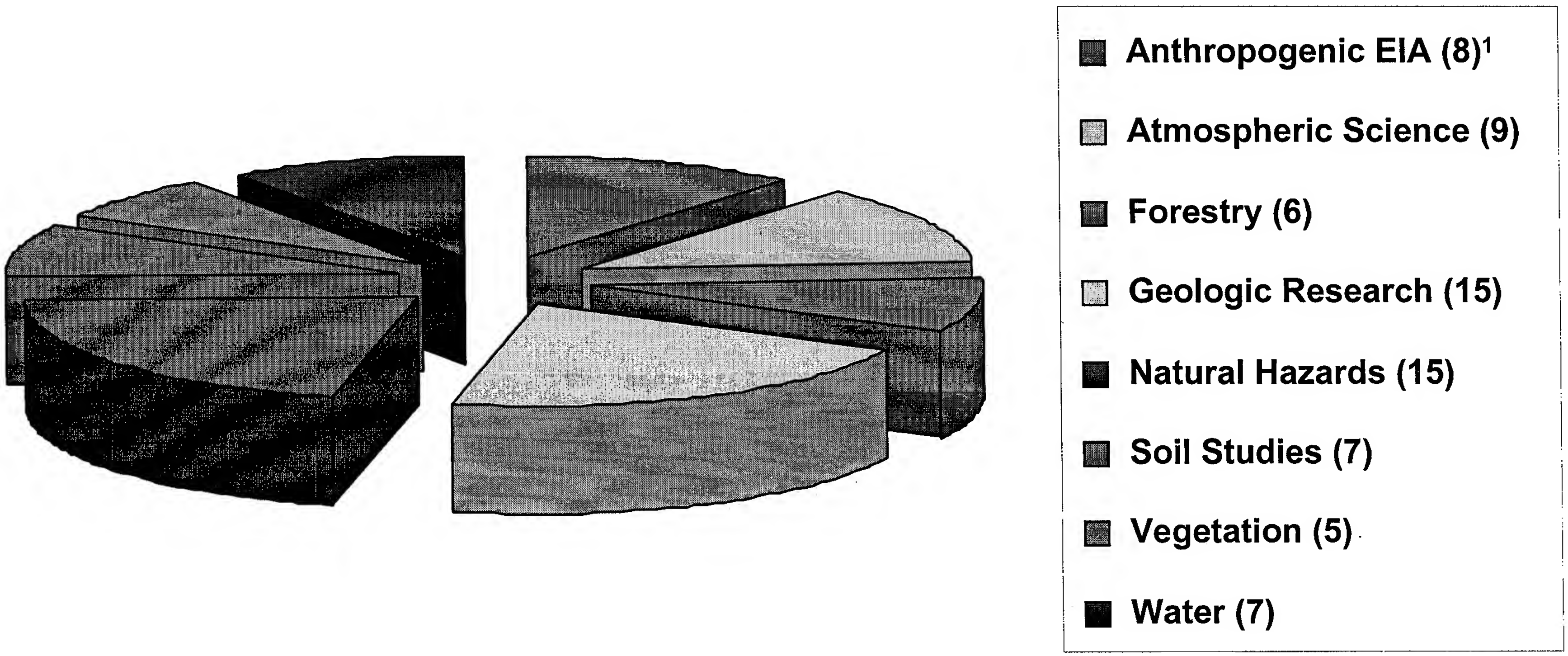
Review on Applications of Landsat Thermal Data

Survey Method:

- Used WWW to survey applications of Landsat thermal data
- Applied Google search engine to survey journal articles, conference papers, reports, and bibliographies
- Focused search on applications of Landsat thermal data for atmospheric, water, and terrestrial studies
- Performed additional searches on specific applications and researchers investigating thermal RS applications
- Also surveyed Landsat, ASTER, and MODIS science team WWW sites
- Developed draft white paper on results of literature review, as well as bibliography of references

General Applications of Landsat 5 Thermal Data

Publication Breakdown by Application Group



[1] number of papers given in parenthesis

Based on ~60 publications - some relevant to multiple applications

Specific Applications of Landsat Thermal Data

- **Anthropogenic EIA**
  - Urbanization
  - Land cover change
  - Land degradation
  - Scaling studies
- **Atmospheric Science**
  - Clouds
  - Greenhouse gases
  - Air pollutants
  - Urban climate
- **Forestry**
  - Forest regeneration
  - Forest wildfires
  - Leaf area index
  - Temperature zonation
  - Scaling studies

- **Anthropogenic EIA (8)**
- **Atmospheric Science (9)**
- **Forestry (6)**
- **Geologic Research (15)**
- **Natural Hazards (15)**
- **Soil Studies (7)**
- **Vegetation (5)**
- **Water (7)**

- **Geologic Research**
  - Desert crusts
  - Earthquake assessment
  - Volcanoes
  - Thermal inertia studies
  - Mineral mapping
- **Natural Hazards**
  - Wildfire
  - Volcanism
  - Coal fires
  - Earthquakes
- **Water**
  - Ground water surveys
  - Lake temperature
  - Thermal plumes
  - Cold and hot springs
- **Soil Studies**
  - Moisture availability
  - Salinity
- **Vegetation**
  - Vigor
  - Growth

Summary of Landsat Thermal Application Survey

- Survey indicated several atmospheric, terrestrial and water applications. Application diversity greater than expected
- Survey revealed no papers comparing Landsat 5 and 7 thermal data for utility
- Many Landsat 7 science team members require thermal data, often for use with other Landsat bands
- One Landsat 7 science team member projected that 60 meter thermal data would improve and increase usage for agricultural and vegetation studies
- Survey also identified publications on sharpening of Landsat 5 thermal data
  - These may be useful if LCDM thermal data has a 120 m GSD

Existing Thermal Architectures

Traditional TIR Architectures

- **Cross-track scanning systems**
- **Cooled either actively or passively**
- **Small number of HgCdTe detectors**
- **Typically large GSD**
  - Landsat is the smallest *(60 m)* of the cross-track scanning systems
- **Telescope diameter typically driven by SNR considerations and not diffraction**
- **Most systems are multispectral**

Existing TIR Systems

Landsat Data Continuity Mission

Satellite	Sensor	Band	Spectral Range [mm]	Telescope Diameter [cm]	GSD [m]	Swath [km]
HgCdTe Pushbroom						
MTI	MTI	L	8.00 - 8.40	36	20	12
		M	8.40 - 8.85	"	"	"
		N	10.20 - 10.70	"	"	"
HgCdTe Cross-track scanners						
Landsat 7	ETM+	6	10.4 - 12.5	40	60	185
Terra	ASTER	10	8.125 - 8.475	24	90	60
		11	8.475 - 8.825	"	"	"
		12	8.925 - 9.275	"	"	"
		13	10.25 - 10.95	"	"	"
		14	10.95 - 11.65	"	"	"
Terra	MODIS	27	6.535 - 6.895	18	1000	2330
		28	7.175 - 7.475	"	"	"
		29	8.400 - 8.700	"	"	"
		30	9.580 - 9.880	"	"	"
		31	10.780 - 11.280	"	"	"
		32	11.770 - 12.270	"	"	"
		33	13.185 - 13.485	"	"	"
		34	13.485 - 13.785	"	"	"
		35	13.785 - 14.085	"	"	"
		36	14.085 - 14.385	"	"	"

Note ETM+ is the only single band instrument!

New Thermal Architectures

New Pushbroom and Framing Camera Thermal Architectures

- **Pushbroom systems and framing cameras can provide significant sensitivity advantages over cross-track scanners**

  SNR ~ *(no. of detectors)*$^{0.5}$

- **The increased integration time associated with pushbroom systems and framing cameras allow:**
  - Higher SNR
  - Smaller GSD
  - Potential use of uncooled detectors

Potential New Configurations

- **Cooled detectors**
  - Advanced Land Imager (ALI) pushbroom architecture *(common telescope for all bands)*
    - ➢ Multispectral Thermal Imager *(MTI)*
- **Uncooled detectors**
  - ALI pushbroom architecture *(common telescope for all bands)*
    - ➢ ALI common telescope and optics
  - Custom TIR system separate from ALI
    - ➢ Framing camera and filter wheel (ISIR)
    - ➢ Pushbroom multispectral system *(THEMIS)*

Infrared Detector Types

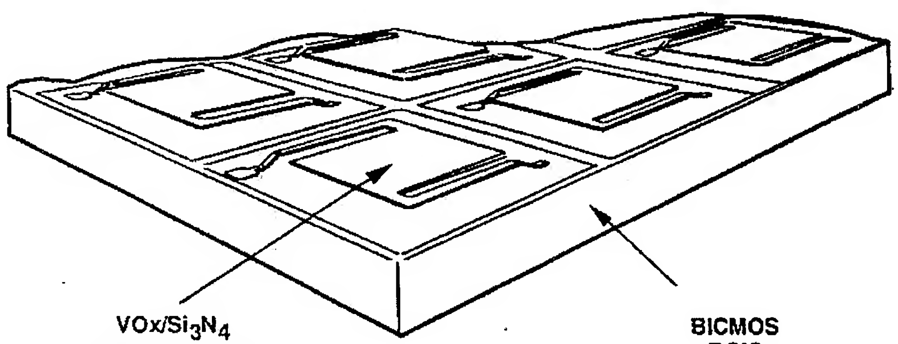
- **Cooled detectors**
  - Photovoltaic or photoconducting mechanisms
    - HgCdTe and GaAs quantum well devices
  - High framing rates and low noise
- **Uncooled detectors**
  - Rely on a thermal response
    - Bolometric, pyroelectric, and thermionic devices
  - Have slow framing rates and are relatively insensitive
  - Lighter and smaller system packaging possible

Uncooled Thermal Detector Characteristics

- **Primarily developed for military systems**
  - f/1 optics, 30-60 Hz framing rates
- **Microbolometers**
  - Silicon micro-machined devices provide excellent thermal isolation from substrate. Highest sensitivity demonstrated: f/1 optics, 30 Hz framing rate, NEDT < 20 mK
- **Pyroelectric**
  - Older technology: f/1 optics, 30 Hz framing rate, NEDT ~ 100 mK
  - Requires a chopper
- **Thermionic**
  - New technology, but holds promise

Silicon Microbolometers

- **Black absorber with a broadband response *(atmospheric window 8-14 microns)***
- **Typical FPA**
  - 320x240 pixels with 50 µm pitch
  - 640x480 pixels with 25 µm pitch
  - Very high fill factor >90%



MICROBOLOMETER PIXEL STRUCTURE

W.Radford, D. Murphy, M. Ray, S. Propst, A. Kennedy, J Kojiro, J. Woolaway, K Soch, "320 x 240 silicon microbolometer uncooled IRFPAs with on-chip offset correction," SPIE Vol. 2746, pp. 82-92.

ALI Architecture with Cooled Detectors

- **Scale-up MTI hardware (One set of trades)**
  - 13 km swath scaled up to 185 km
  - Aperture kept to 36 cm
  - 20 m GSD scaled up to 60 m
  - NEDT 0.2-0.3 °K or better
  - ~3000 pixels across *(6 modules of 512 pixels each)*
    - ~25 cm long TIR focal plane
  - ~7 yr expected lifetime with redundant refrigerant system
    - Too many detectors to be passively cooled
  - ~$50M-$100M for 2-3 multispectral thermal bands
    - A few additional thermal bands will not significantly increase cost
    - Cost dominated by cooled detectors
    - Cost model does not fully account for commonality with other ALI bands

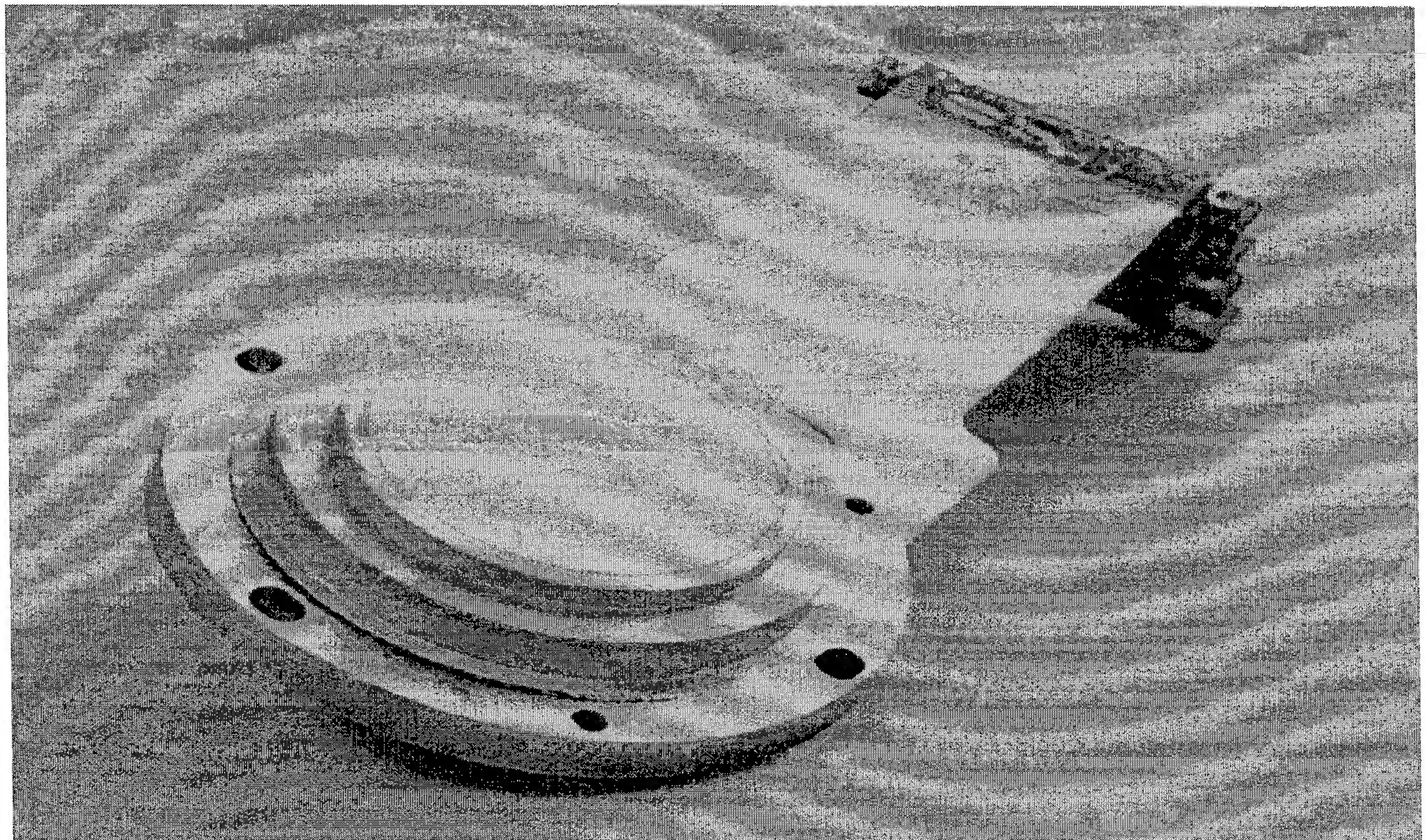
Uncooled Framing Camera/Pushbroom Pathfinding Thermal Instruments

- **Infrared Spectral Imaging Radiometer *(ISIR)***
  - Flown on space shuttle mission STS-85 August 1997 as part of a cloud science experiment
  - Uncooled Lockheed Martin microbolometer array *(327x240 pixels)*
    - Framing imager with filter wheel
    - 3 narrow bands at 8.55, 10.8 and 11.8 µm
    - 1 broad band at 7-13 µm
    - 250 m GSD
    - 85 km swath from shuttle altitude
    - f-number 0.73, Len diameter 50 mm
    - NEDT 0.01-0.06 °K at all wavelengths with TDIx40 for a 300 °K scene temperature
    - Ambient and cold inflight calibration capability
  - Extremely good quality imagery was obtained for each band
  - Accuracy goal was met to within a factor of 2 or 3
    - Pre-production prototype detector used

Uncooled Pushbroom Pathfinding Thermal Instruments

- **Thermal Emission Imaging System IR Sensor *(THEMIS)***
  - Flown on Mars 2001 Orbiter, launched April 2001, to map Martian surface mineralogy
  - Uncooled Raytheon microbolometer array *(320x240 50 µm pitch pixels)*
    - ➢ Pushbroom imager with precision-aligned stripe filter
    - ➢ 9 bands between 6.2 and 15.5 µm
    - ➢ f/1.6 optics
    - ➢ 4.4 degree FOV
    - ➢ 12.9 cm aperture
    - ➢ 30 Hz readout
    - ➢ 100 m GSD
  - ~ $12M for instrument

THEMIS FPA Assembly



D.Murphy, W. Radford, J. Finch, A. Kennedy, J. Wyles, M. Ray, G. Polchin, N. Hua, C. Peterson, "Multi-spectral Uncooled Microbolometer Sensor for the Mars 2001 Orbiter THEMIS Instrument," Proceedings of IEEE Aerospace Conference Big Sky, Montana.

New Thermal Architecture Sensor Trades

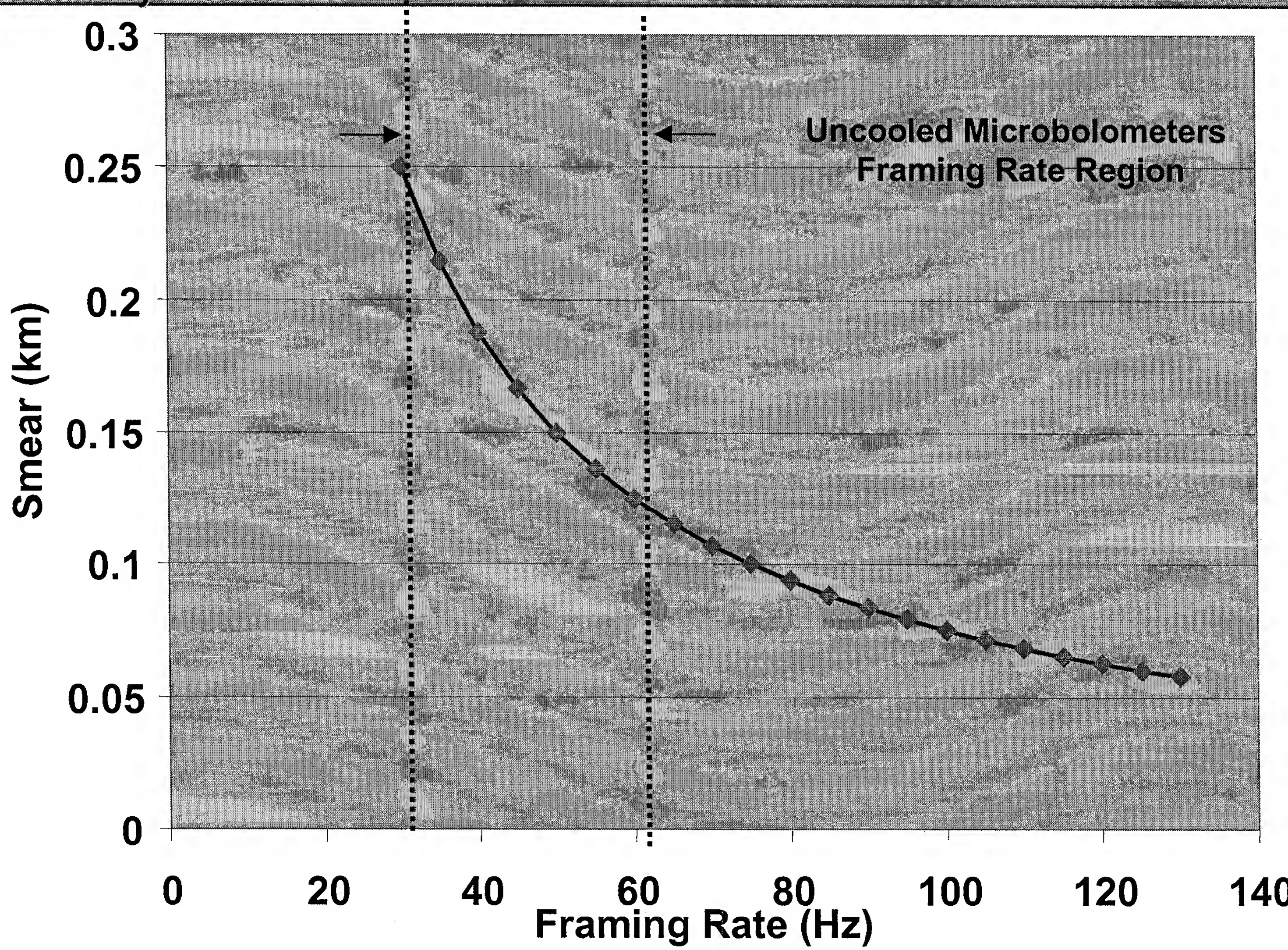
Thermal GSD Trades

- **GSD usually set to approximately FWHM of Point Spread Function (PSF)**
- **Two sensor characteristics drive PSF**
  - Framing rate
    - Smear is defined as how far a pixel moves in an integration time
    - Typically GSD ~ Orbital Velocity / Frame Rate
  - Telescope diameter
    - Ground spot size for a diffraction limited system is controlled by Airy Diffraction Pattern
    - Ground spot size ~ 2.44 Wavelength* Range / Telescope Diameter

Frame Rate Trades for Landsat Orbit

Landsat Data Continuity Mission

Framing Rate Hz	Smear m
30.00	250.1
35.00	214.3
40.00	187.5
45.00	166.7
50.00	150.0
55.00	136.4
60.00	125.0
65.00	115.4
70.00	107.2
75.00	100.0
80.00	93.8
85.00	88.3
90.00	83.4
95.00	79.0
100.00	75.0
105.00	71.4
110.00	68.2
115.00	65.2
120.00	62.5
125.00	60.0
130.00	57.7

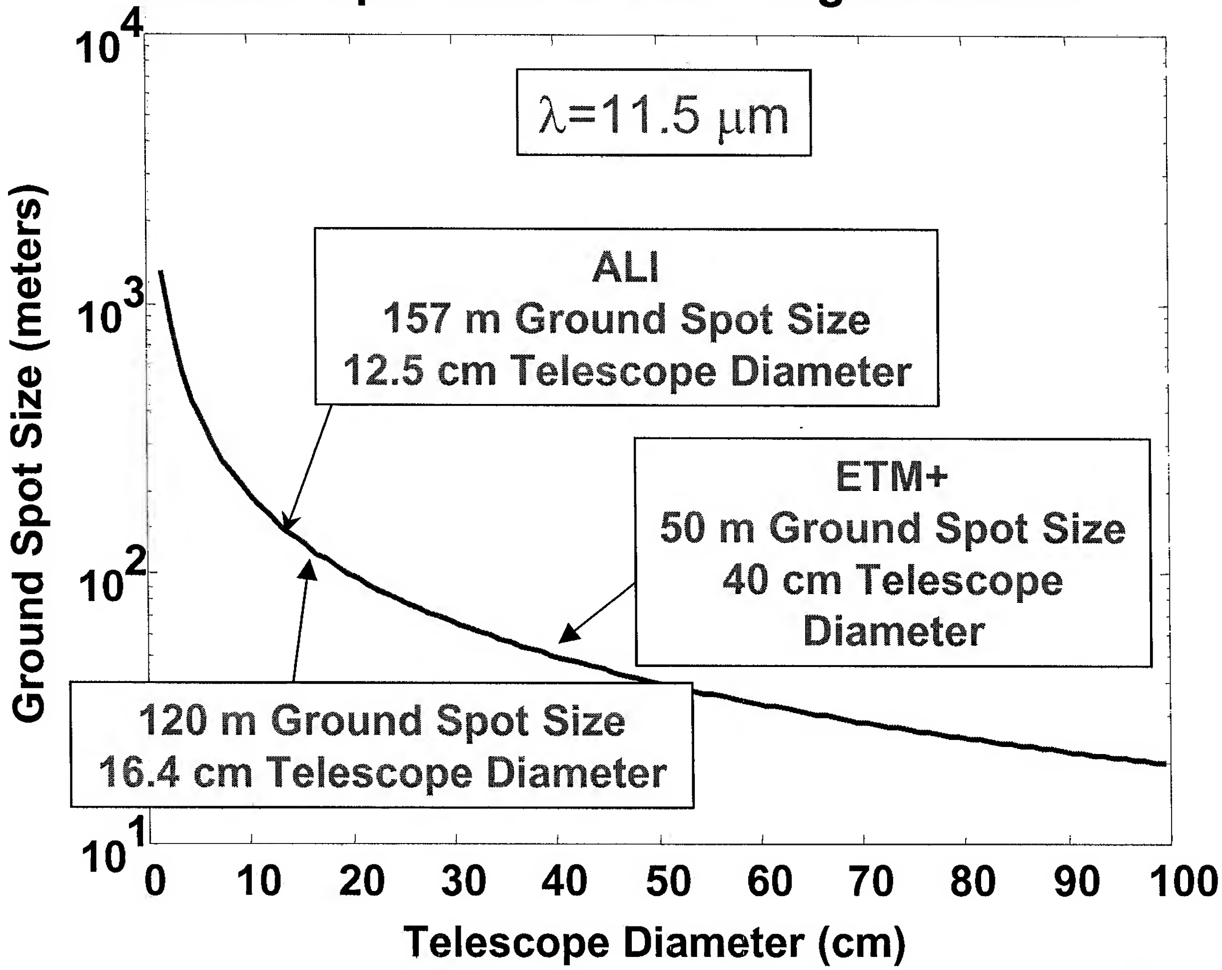


60 Hz Framing Rate Limits Smear to 125 meters

Telescope Diameter Trades

Diffraction limited resolution *(Rayleigh criteria)*

Ground Spot Size= 2.44 λ Range/Diameter



ALI Architecture with Uncooled TIR Detectors

ALI Architecture Trade Space Assumptions

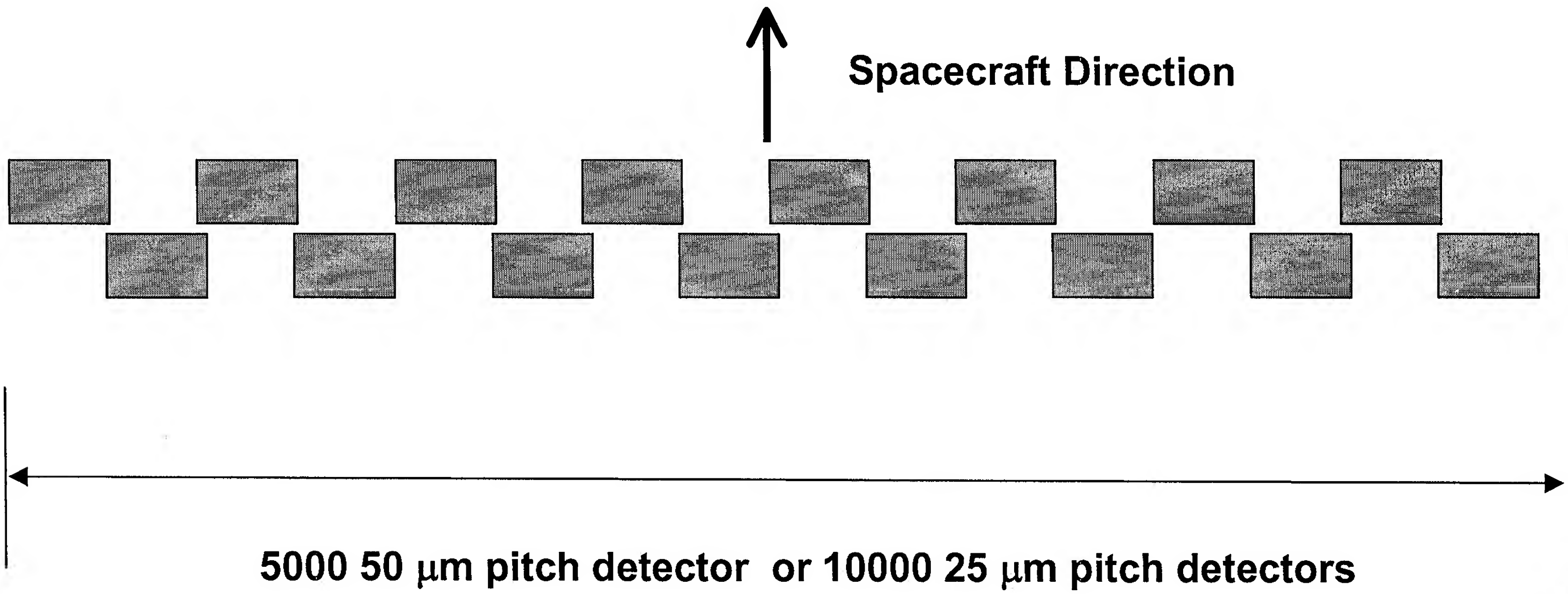
- **No significant non-recurring engineering for focal planes**
  - Initial design limited limited to 60 Hz framing rate
- **Fixed f-number of 7.5**
- **Fixed aperture diameter of 12.5 cm**
- **Diffraction limited telescope at center wavelength *(11.5 μm)***
- **Sufficient room to add a double bank of 320x240 50 μm or 640x480 25 μm microbolometer arrays to ALI system**
- **Approximately 100 mK NEDT for a 10.4-12.5 μm 300 K source (based on a f/1 optic, 30 Hz framing rate, 8-14 μm band having 20 mK NEDT)**
- **Desired NEDT ~0.5 K for 300 K background**
- **Infrared thermal source can be inserted in front of the optics for calibration**

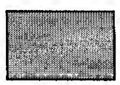
ALI Architecture with IR Uncooled FPA

- **Focal Plane Spot size = 2.44 * f # * λ = 210 μm**
- **Ground Spot size at a 705 km orbit is 157 m**
- **16 FPAs are necessary for both 25 and 50 μm pitch detectors *(185 km swath)***
  - Approximately 5000 for 50 μm pitch detectors
  - Approximately 10000 for 25 μm pitch detectors
- **Approximately 37.6 m GSD for a single 50 μm pitch detector and 18.8 m GSD for a single 25 μm pitch detector**

Possible FPA Configuration

Double Bank of Uncooled Microbolometer Detector Arrays




320x240 or 640 x480 Detector FPA

NEDT Scaling

- **Everything scaled to f/1 optics, 8-14 μm band and 30Hz framing rate with 20 mK NEDT**
  - Newer configurations may reach 10 mK NEDT
  - **Calculations are only good to about a factor of 2**
- **NEDT scales as (f-number)^2**
  - **Scale factor 56 for f7.5 ALI optics**
- **NEDT scales as (spectral bandwidth)$^{-1}$**
  - Scale factor = 2.7 for 10-4-12.5 μm band
  - Conservative since detector rolls off faster at end of spectral band
- **NEDT scales as ~(framing rate)$^{-1}$**
  - Scale factor =2
  - May require using 25 μm detectors to overcome thermal time constant and other effects

NEDT Scaling

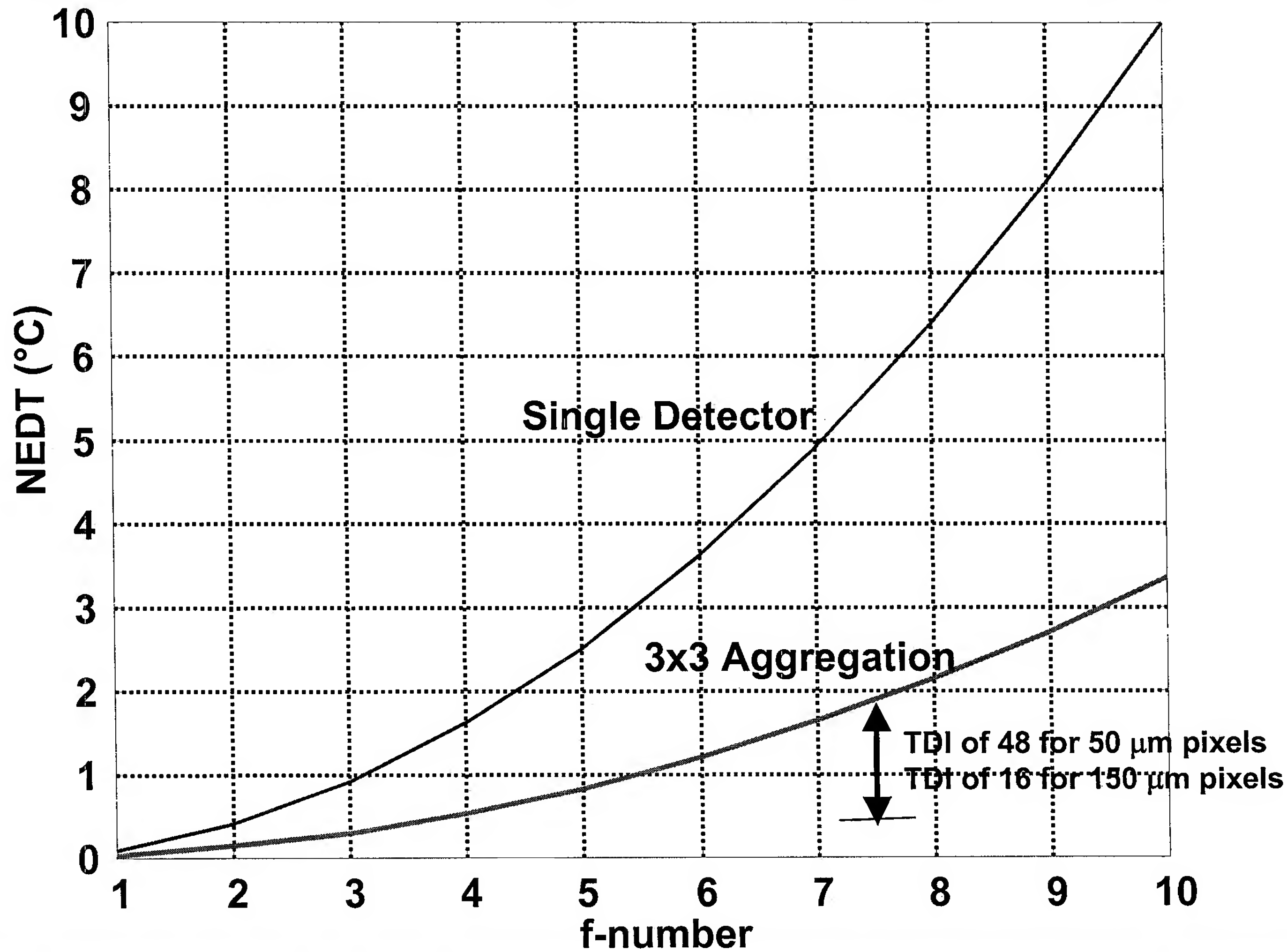
- **NEDT scales as (No. of pixels averaged)$^{0.5}$**
  - NEDT for a single pixel =5.4 K
  - Requires ~116 pixels to average to achieve 0.5 K

NEDT Improvements

- **TDI**
  - Maximum theoretical improvement of about 15 for 240 pixels
  - NEDT improves as (No. of TDI pixels)$^{0.5}$
- **Pixel aggregation**
  - NEDT improves (No. of pixels aggregated) $^{0.5}$
- **Point design**
  - Aggregation
    - ➢ 3x3 aggregation
    - ➢ Corresponds to 112m x112 m pixel
  - TDI of 48 to achieve 0.5 K
    - ➢ TDI of 16 for 3x3 aggregation
- **Other possibilities should be analyzed but the above approach could provide Landsat 5 like thermal imaging performance**

NEDT Scaling with F#

Single detector NEDT 100 mK for f/1, 60 Hz readouts, 10.4-12.5 μm

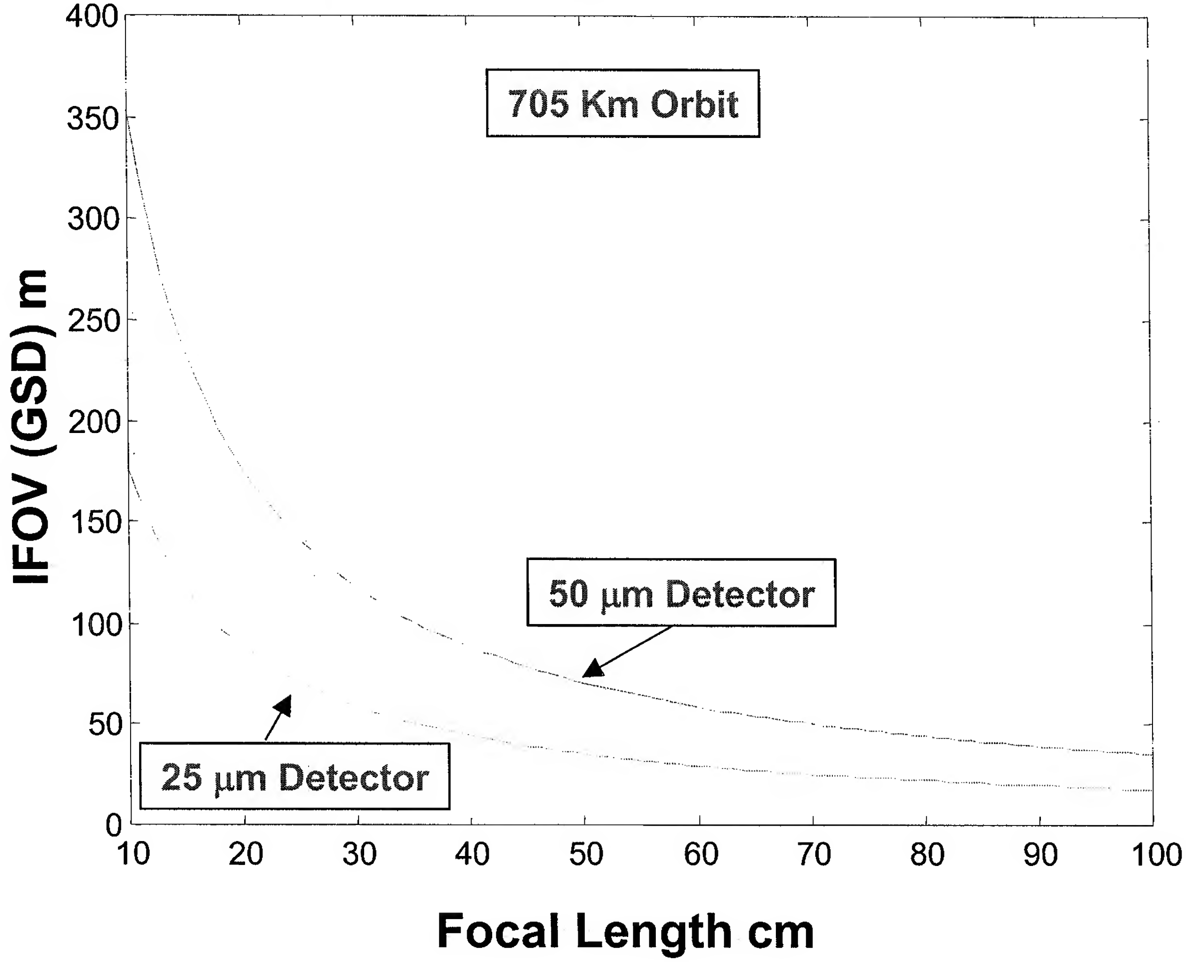


Custom TIR Sensor (Point Design)

- **Assume new telescope and sensor separate from ALI**
  - Assume 120 m spatial resolution desired
- **125 smear on ground (60 Hz readout)**
- **Aperture ~16.4 cm**
  - 120 m Ground Spot Size
- **Focal Length ~29.4 cm**
  - 120 m GSD for 50 μm detectors
  - 60 m GSD for 25 μm detectors

Focal Length Trade

GSD (IFOV)= Range*(Detector/Focal Length)



Custom TIR Sensor (Point Design)

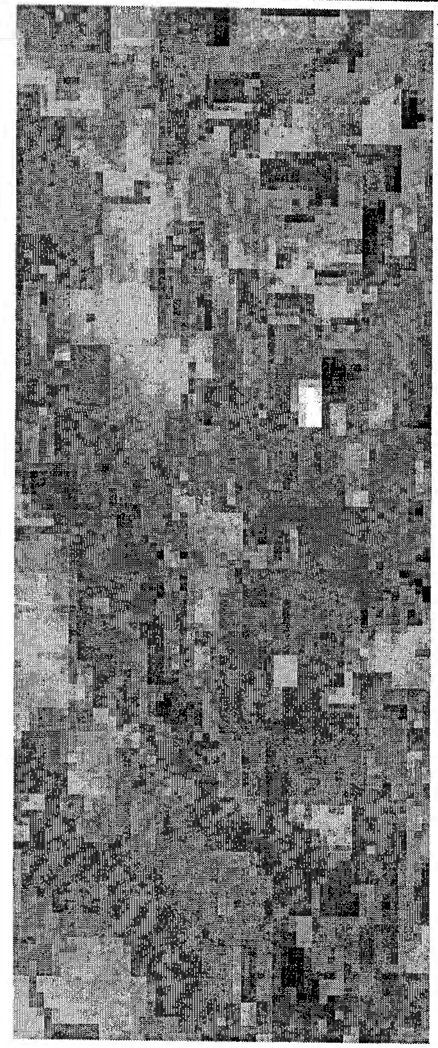
- **F-number 1.8**
  - A little fast but probably achievable (THEMIS f-number 1.6)
- **NEDT for Landsat Band 300 K Background**
  - NEDT of a single detector ~ 0.3 K with a TDI of 1
  - TDI of 25 could produce a 0.06 K NEDT system!!!!
- **Detector spot size 50.5 μm at λ=11.5 μm**
  - ~1542 detectors at 50 μm pitch for 185 km swath with 120 m GSD
  - ~Five 320x240 FPAs
- **Many detectors available for other bands**
  - ASTER like instrument
  - Oversampling
    - ➢ Use 25 μm pitch detectors and over sample PSF

Simulated Thermal Imagery Using ATLAS 10.4-12.5 μm Band Over Brookings SD

60 m GSD
70 m PSF

30 m GSD
110 m PSF

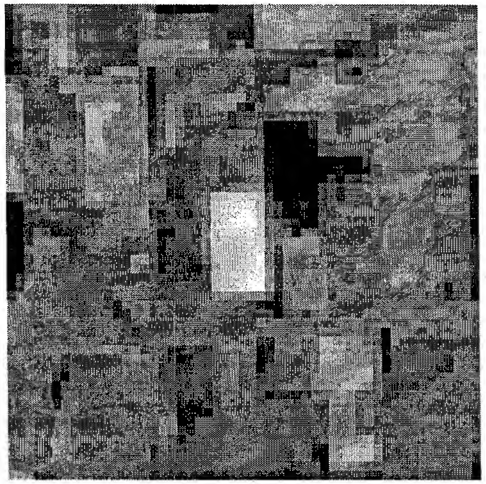
60 m GSD
110 m PSF



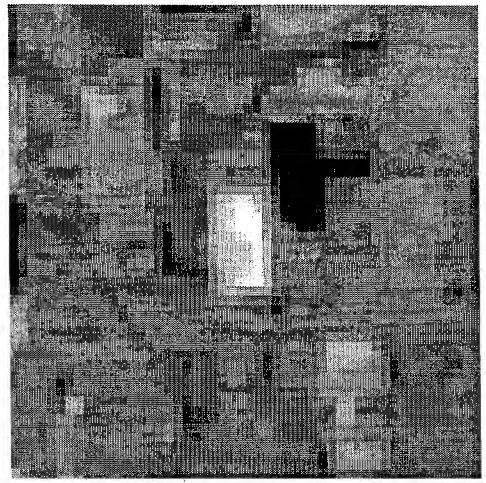
120 m GSD
110 m PSF

Simulated Thermal Imagery

Landsat Data Continuity Mission

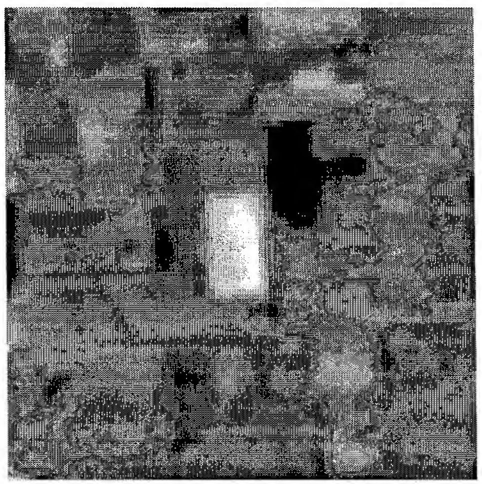


ETM+ 60 m GSD
70 m PSF

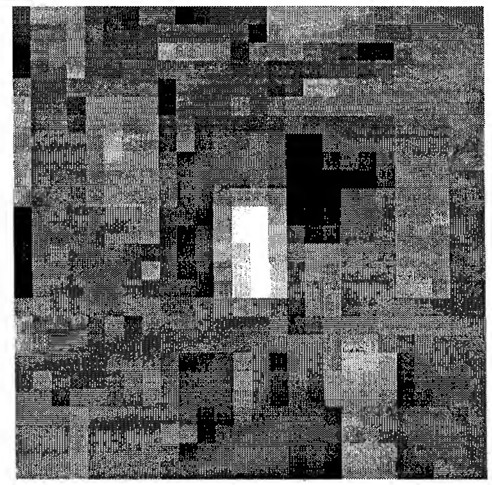


60 m GSD
110 m PSF

30 m GSD
110 m PSF



MSS 120 m GSD
110 m PSF



Oversampled imagery partially recovers spatial resolution enabling smaller telescope (ALI) and slow framing rates could still produce high quality imagery

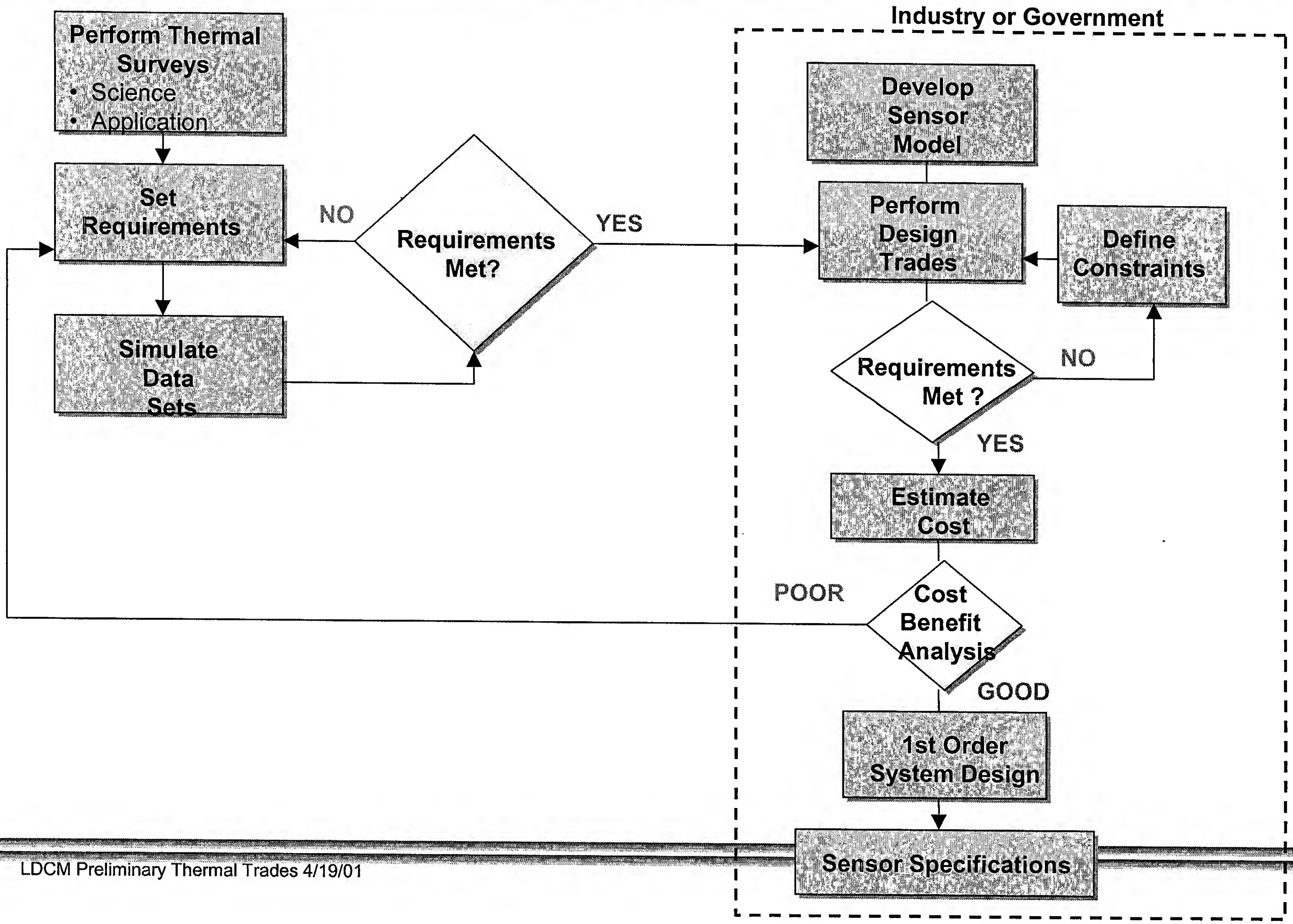
Conclusions

- **Multispectral pushbroom thermal systems have already been flown in space**
  - MTI
- **Uncooled microbolometers cameras have already been flown in space or soon will be**
  - ISIR
  - THEMIS
- **Current technology uncooled Si microbolometers could provide approximately 120 m GSD data with NEDT <0.5 C in an ALI pushbroom architecture**
  - PSF limited by framing rates of OTS electronics
  - Future systems could attain 60 m GSD with oversampling
  - Approximately ~20 M$ (TBR) additional cost on an ALI system
  - Independent SBRC estimate 0.33 K sensitivity possible with 245 K background

Conclusions Continued

- **Initial analysis shows a custom designed uncooled thermal system could be extremely sensitive**
  - Approximately ~20 M$ (TBR) sensor
  - Multispectral thermal capability adds incremental cost to a single band thermal system
  - Oversampling could provide near ETM+ capability without large telescope and custom electronics
  - Custom electronics could potentially provide 60 m smear with reasonable sensitivity
  - Could be combined with atmospheric correction bands

Next Steps Flow Chart



Next Steps-System Engineering Approach

- **Perform thermal surveys**
  - Continue thermal applications literature survey
  - Speak with ASTER, MODIS and AVHRR communities
- **Set requirements**
  - NEDT, PSF, GSD, aliasing, spectral band(s), etc
- **Simulate data sets**
  - Utilize NASA SSC ATLAS and other airborne thermal systems
  - Model sensor parameters using generated requirements
- **Evaluate requirements**
  - Evaluate simulated imagery
  - Solicit thermal community input

Next Steps, Continued

- **Develop sensor model**
  - Modify existing physics-based algorithms to model sensor hardware
- **Perform sensor design trades**
  - Telescope diameter, f#, detector pitch, readout noise, TDI, etc
  - Calibration techniques
- **Estimate system cost**
  - Continue dialog with industry
  - Utilize standard cost estimation models

Backup

Existing Space-based Uncooled TIR Instruments

- **Thermal Emission Spectrometer *(TES)***
  - Flown on Mars Global Surveyer, launched November 1996 and completed its primary mission Jan 2001
  - Uncooled pyroelectric array *(3 sets of 2x3 pixels)*
    - ➢ Michelson Interferometer *(6.25-50 microns)*
    - ➢ 2 broad band channels at 0.3-2.7 and 4.5-100 microns
    - ➢ 3 km ground sample distance at Nadir
    - ➢ 24.9x16.6 mrad Field of View
    - ➢ 8.3 mrad pixel size

ALI Parameters

- **Telescope features**
  - 12.5 cm entrance pupil
  - 15 Degree x 1.26 Field-of-View
  - Telecentric, f7.5 design, focal length 93.73 cm
  - Unobscured, reflective optics

- **Orbit**
  - 705 Km sun synchronous with 10:01 AM descending node time

Existing TIR Systems

Satellite	Sensor	Architecture	Band	Spectral Range [μm]	Detector Material	Telescope Diameter [cm]	Spatial Resolution GSD [m]	Spatial Resolution MTF @ Nyquist	Swath [km]	Quant. [bit]	NEΔT [K]
Landsat 7	ETM+	Cross-track scanner	6	10.4 - 12.5	HgCdTe	40	60	0.3	185	8 of 9	
Terra	ASTER	Cross-track scanner	10	8.125 - 8.475	HgCdTe	24	90	0.35	60	12	0.2
			11	8.475 - 8.825			"		"	"	"
			12	8.925 - 9.275			"		"	"	"
			13	10.25 - 10.95			"		"	"	"
			14	10.95 - 11.65			"		"	"	"
NOAA	AVHRR	Cross-track scanner	4	10.3 - 11.3	HgCdTe	20	1100	0.3	2800	10	0.12
			5	11.5 - 12.5			"		"	"	"
Terra	MODIS	Cross-track scanner	27	6.535 - 6.895	HgCdTe	18	1000	0.35	2330	12	0.25
			28	7.175 - 7.475			"		"	"	0.25
			29	8.400 - 8.700			"		"	"	0.05
			30	9.580 - 9.880			"		"	"	0.25
			31	10.780 - 11.280			"		"	"	0.05
			32	11.770 - 12.270			"		"	"	0.05
			33	13.185 - 13.485			"		"	"	0.25
			34	13.485 - 13.785			"		"	"	0.25
			35	13.785 - 14.085			"		"	"	0.25
			36	14.085 - 14.385			"		"	"	0.35
MTI	MTI	Pushbroom	L	8.00 - 8.40	HgCdTe	36	20		12	12	0.025
			M	8.40 - 8.85			"		"	"	0.027
			N	10.20 - 10.70			"		"	"	0.045
ERS-2	ATSR-2	Conical scanner	1	11.5 - 12.3		11	1100		500	12	0.02
			2	10.6 - 11.3			"		"	11	"